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A Comparison of Post-processed Variables used by the Tri-Service Version of the Integrated Weather Effects Decision Aid

by Jeffrey Passner

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14. ABSTRACT

The U.S. Army Research Laboratory (ARL) has developed a "red-amber-green" mission-planning aid for Army commanders to advise them when and where the environmental conditions currently exceed or are forecasted to exceed levels of "marginal" or "severe" impact to their systems, operations, or personnel. A Tri-service version of the software has been developed and fielded on Air Force and Navy systems. Meteorological data is provided to the Tri-Service Integrated Weather Effects Decision Aid (T-IWEDA) from both the Weather Research and Forecasting (WRF) model and ½-degree Global Forecast System (GFS) output. Once the model output is received, many of the weather variables needed by the T-IWEDA rules are developed by both Air Force Weather Agency (AFWA) and ARL in their post-processing software so that mission planning can be achieved based on the weather conditions. This report looks at the different and unique approaches to solving forecasting challenges such as clouds, icing, and turbulence.

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1. Summary

The U.S. Army Research Laboratory (ARL) has developed a “red-amber-green” mission-planning aid for Army commanders to advise them when and where the environmental conditions currently exceed or are forecasted to exceed levels of “marginal” or “severe” impact to their systems, operations, or personnel. A Tri-service version of the software has been developed and fielded on Air Force and Navy systems. Meteorological data is provided to the Tri-Service Integrated Weather Effects Decision Aid (T-IWEDA) from both the advanced version of the Weather Research and Forecasting-Air Force Weather (WRF-AFW) model and ½-degree Global Forecast System (GFS) output. Once the model output is received, many of the weather variables needed by the T-IWEDA rules are developed by both Air Force Weather Agency (AFWA) and ARL in their post-processing software so that mission planning can be achieved based on the weather conditions. This report looks at the different and unique approaches to solving forecasting challenges such as clouds, icing, and turbulence.

2. Introduction

ARL has developed mission-planning guides for the Army to provide weather information and how it will impact systems, operations, or personnel. A Tri-service version of the software has been developed and fielded on Air Force and Navy systems. Meteorological data is provided to the T-IWEDA from both the WRF model and ½-degree GFS output. ARL has performed research involving various aspects of the WRF model (Skamarock et al., 2008) version 3.0.1.1 in recent years while in a similar fashion AFWA has also used the WRF for short-term forecasts and the GFS for long range forecasts. The models provide forecasts for temperature, pressure, moisture, wind, precipitation amounts, and many other variables; however, many of the weather variables needed by the T-IWEDA are not available directly from the models. These variables include icing, turbulence, surface visibility, cloud heights, thunderstorm probability, and numerous others. To meet the needs of T-IWEDA, these parameters are formulated by ARL and AFWA after the model is completed, or in a post-processed manner. While many of the techniques used by ARL and AFWA are similar, the goals of AFWA and Army weather are dissimilar; with the Army needing weather information at smaller scales in both time and space. Thus, there are differences in the way they approach the post-processing variables and it becomes essential to investigate how and why AFWA and ARL develop post-processed parameters.

3. IWEDA Summary

The Integrated Weather Effects Decision Aid (IWEDA) is successfully deployed today with the U.S. Army Combat Weather Teams (CWT) around the world for Command and Control; Battle Command; and Command, Control, Communications, Computers and Intelligence, Surveillance and Reconnaissance mission planning applications. Meteorological weather effects critical values are those values of weather factors that can significantly reduce the effectiveness of tactical operations and or weapon systems. These operational limits are usually based on tests conducted during weapon system development or on the operational experience of weapon system users. The critical threshold is where the occurrence of a meteorological element causes a significant degradation or impact on a military operation, system, subsystem, or on personnel (Hoock, 2010).

Mission planners must be aware of weather factors that will affect their operations, ensuring the greatest chance of mission success. They must be familiar with meteorological critical thresholds to effectively use weapon systems and other assets, and to provide maximum safety for friendly personnel. Conversely, weather support personnel can use the critical values to familiarize themselves with the weather elements that require extra examination while preparing forecasts. Meteorological critical values are the lowest common denominator in assessing: (a) weather support requirements; (b) specific effects of weather on any system, subsystem, operation, tactic, and personnel; and (c) who has the tactical advantage in adverse weather–friendly or threat forces. Critical values have many important applications in the intelligence preparation of the battlefield, models and simulations, training, and in military decision aids like IWEDA.

The IWEDA is a rules-based expert system based on thousands of identified and validated weather sensitivities of Army, Air Force, Navy, and foreign threat weapons systems and tactical operations. IWEDA is tailored to specific tactical operations and missions, and provides detailed weather impacts information in terms of what operations and equipment are effected, as well as when, where, and why they are affected. A dynamic rule editor allows the CWT to modify the rules or critical values for certain purposes. A “what-if” war-gaming feature allows the user to look at alternative mission or system setups and weather conditions. The Integrated Meteorological System’s (IMETS’s) gridded database automatically drives the IWEDA.

In order to satisfy the “rules,” IWEDA needs a number of meteorological variables. At the surface this includes cloud, moisture, temperature, precipitation, visibility, pressure, and wind direction and speed information. Upper-air data includes clouds, moisture, icing, pressure, temperature, turbulence, and wind values.

4. Modeling and Post-Processing

4.1 AFWA Modeling

In recent years AFWA has transitioned from the Pennsylvania State University/National Center for Atmospheric Research (NCAR) Mesoscale Model 5 to the Advanced Research version of the WRF. However, the goal of AFWA modeling is very broad with a requirement to cover the entire globe with forecast needs from the initial time to ten days.

To meet these long-range goals AFWA receives GFS model data from the National Center for Environmental Prediction (NCEP). The GFS is a global spectral data assimilation and forecast model system with products available every 6 h at 00, 06, 12 and 18 Coordinated Universal Time (UTC). The horizontal resolution is roughly equivalent to 0.5×0.5 degrees latitude and longitude. The vertical resolution is currently 64 layers, with enhanced resolution near the bottom and top, as well a model top at 0.2 hecto-Pascal (hPa). The GFS contains a full suite of parameterized physics as well as accompanying sea-ice and land-surface models.

For shorter range forecasts and for higher resolution windows across the globe, the AFWA WRF uses fully-compressible and non-hydrostatic equations, and is conservative for scalar variables. The horizontal coordinate is the Arakawa staggered C-grid, while a terrain-following mass coordinate is used. Both 1-way and 2-way nesting are supported, with an option for moving nests. A number of microphysical schemes, cumulus parameterizations, land-surface models, and Planetary Boundary Layer (PBL) schemes can be applied to the model. WRF executes efficient execution on a range of computing platforms (distributed and shared memory, vector and scalar computing). The scientific code is separated from the parallelization and other architecture-specific codes. WRF is highly modular, using single-source Fortran-90 code for maintainability. It supports multiple dynamics solvers and physics modules. WRF's model coupling application programming interface enables it to be coupled with other models such as ocean, and land models (see Weather Decisions Technologies in references).

The following schemes and parameterizations are used in the AFWA version of the WRF-ARW

- 3rd order Runge-Kutta dynamics
- 19-km model top
- Kain-Fritsch convective parameterization
- Medium Range Forecasts Planetary Boundary Layer scheme
- Lin microphysics
- Rapid Radiative Transfer Model (RRTM) longwave radiation

- Dudhia shortwave radiation
- Thermal diffusion surface physics
- 15- and 5-km grid length depending on area and forecasting needs

4.2 ARL WRF Modeling

ARL has initiated a full set of research experiments to investigate the WRF model at scales ranging from cloud-to-storm. The focus is on modeling scales to 1 km or finer grid spacing, minimal nesting, lateral boundary conditions supplied from operational mesoscale models such as North American Model or AFWA's WRF, and limited model domain sizes. Successful development of such a capability, called a Weather Running Estimate-Nowcast (WRE-N) would provide the Army with a method to rapidly update and "nowcast" the local battlefield meteorological conditions out to 3 h (Dumais et al., 2009).

The specifications of the ARL WRF nests, along with a control set of namelist (model control) options, are shown in table 1.

Table 1. Namelist options for WRF-ARW control run used in this model study.

Namelist Parameter	Option Selected
Shortwave radiation scheme	Dudhia scheme
Longwave radiation scheme	Rapid radiative transfer model
Explicit moist microphysics	WRF Single Moment-5 (WSM-5) class
Cumulus parameterization	None
PBL scheme	Yonsei State University non-local closure
Surface layer	Monin-Obukhov
Land surface scheme	NOAH land-surface model
Time step (sec) to grid-spacing (km) ratio	3:1
Horizontal subgrid diffusion	2nd order on coordinate surfaces
Subgrid turbulence closure	Horizontal Smagorinsky 1st order closure
Number of vertical eta-pressure (etap) terrain-following levels	60
Vertical velocity damping	Yes
Feedback	Yes–with smooth-desmooth-smooth filter
Nesting	Two-way
Terrain slope/shadow	Yes

4.3 Post-Processing

Most mesoscale models produce forecasting parameters such as temperature, pressure, moisture, and wind speed and wind direction at both the surface and aloft. While these outputs provide valuable weather information for users, T-IWEDA and many other tactical decision aids have a need for additional parameters such as icing, clouds, thunderstorms, surface visibility, and clear-air turbulence. Due to computation time, model dynamics, and user needs it is common to produce many of the "sensible" weather products after the model has completed. The raw output files from the model can be used to derive these vital weather parameters (Passner, 2003).

There are a number of different approaches to post-processing. The meteorological variables can be produced through statistical routines, through artificial intelligence theory, empirical methods, or a combination of methods. Verification is often difficult. As an example, some of the original products such as turbulence were developed for upper-air forecasts at a single point. The turbulence routine was then used for mesoscale models and transitioned from larger scales such as 15-km to smaller scales as 1-km horizontal resolution. Turbulence forecasts were found to be ineffective at smaller scales since turbulence is scale dependent; thus, different routines had to be developed for smaller resolutions. Additionally, AFWA had a mismatch of input data since they were using both the WRF and GFS, which contained different model outputs at different resolutions. Thus, AFWA needed to post-process certain variables for the WRF but not for the GFS. It would have been a simple process for AFWA to simply produce all the post-processing, but AFWA's needs were dissimilar to those of ARL. ARL's emphasis on the boundary layer meant that it needed a value for inversion heights at every grid point, a product that AFWA did not produce. In addition, another obstacle was that AFWA could not transmit large data sets to ARL in a timely fashion due to the vast numbers of variables needed by ARL for T-IWEDA. ARL developed many of these variables "in house." This means that AFWA and ARL often have different approaches to solve the same problem due to the numerous methods that can be used to post-process the model output as well as the different scales needed by each branch of the military. Even using the same model (WRF) the results for such variables as icing and clouds can be different. On the other hand, variables such as precipitation type are the same. It becomes necessary to investigate how and why these routines are different.

As a first step, ARL checks to see if the post-processed variables are available from AFWA. To receive the available AFWA-derived post-processed variables ARL makes calls using the Joint Mission Essential Meteorological and Oceanographic Center *(METOC)* Meteorology and Oceanography Broker Language (JMBL) where JMBL is a specification for a standard language that will broker the exchange of information between METOC data providers and user applications. The JMBL allows for a standardized interface to access METOC data for users and their applications. The way this information is exchanged is with a Web service. It uses unified schema and community of interest semantics to promote interoperability between METOC data consumers and producers. The JMBL is implemented in Extensible Markup Language with a distinct separation between an information retrieval "request" and a "response" to the request.

The entities defined in the Joint METOC Conceptual Data Model (JMCDM) are encapsulated in the JMBL and returned as an instance in the "response" section of the JMBL (see Department of Defense METOC Data Administration in references).

Overall, IWEDA employs 45 variables for the current set of rules. Twenty seven are surface-based parameters (two-dimensional) and 18 are three-dimensional values. Using the WRF data, roughly half of the variables come from AFWA and half are post-processed by ARL. From the GFS, most of the variables are post-processed by ARL as AFWA has no upper-air post-processed data available for the GFS.

5. Differences of the Main Variables in Post-Processing

There are significant differences in the approach and software routines in the post-processing routines of AFWA and ARL. They are discussed in this session.

5.1 Precipitation Forecasts

Precipitation forecasts include thunderstorms, severe thunderstorms, precipitation total, precipitation rates, precipitation flags, and precipitation type forecasts.

5.1.1 Thunderstorms

Both AFWA and ARL base their thunderstorm predictions on equations using statistical methods. AFWA uses the Thunderstorm Prediction Index (TPI) as described by Ellrod and Knapp (1992). The routine is based on the K-index, Best Lifted Index (BLI), Severe Weather Threat (SWEAT) index surface pressure, and precipitable water (PW). Since certain meteorological variables such as the SWEAT index and K-index cannot be calculated at 850 hPa and lower surface pressures, two different equations were developed: one for “low elevations” and one for “high elevations,” where low elevations were considered locations where the surface pressure was greater than 850 hPa and high elevations were locations where the surface pressure was less than 850 hPa. AFWA uses just these two equations to make a “YES/NO” thunderstorm forecast.

Low elevation equation:

$$\text{Thunderstorm Potential}=(0.1795+0.073*(\text{K-index})-0.0149*(\text{BLI})+0.0008*\text{SWEAT})*100. \quad (1)$$

High elevation equation:

$$\text{Thunderstorm Potential}=(0.2101+0.7611*(\text{PRCPWTR}/25.4)-0.054*(\text{BLI}))*100. \quad (2)$$

The ARL routine uses the SWEAT index, Total Totals (TT), K-index, Relative Humidity Average (RHAVE), Showalter Index, Surface lifted index (LI), Convective Available Potential Energy (CAPE), and PW to calculate the thunderstorm probability or potential.

Low elevation equation:

$$\text{Thunderstorm Potential}=(0.1795+0.073*(\text{K-index})-0.0149*(\text{LI})+0.0008*\text{SWEAT})*100. \quad (3)$$

High elevation equation:

$$\text{Thunderstorm Potential}=(0.1436+0.381*(\text{PW})-0.053*(\text{LI})+0.0065*\text{RHAVE})*100. \quad (4)$$

The ARL thunderstorm program has a series of additional checks to more realistically forecast the thunderstorm probability based on different atmospheric environments. As an example, if the equations forecast a 70% chance of thunderstorms, but the sounding displays a capping inversion at 700 hPa the chance of thunderstorms will be reduced. A condition, such as a cap, cannot be determined by the regression equations and stability parameters. Following is a list of ARL "checks" in tables 2 and 3.

Table 2. ARL Thunderstorm probability adjustments for low-elevation stations.

Checks for thunderstorm probability for surface pressure >850 hPa (low-elevation stations)
Looks at time of the day. Assign a value of 1 to 6 to add or subtract thunderstorm probability. Find the month of year for thunderstorm bias (northern and southern hemisphere)
Looks for cold surface temperature which reduces severe thunderstorm probability
Checks the average relative humidity from the surface to 500 hPa
Look at the lifted index and dew point to keep consistency
Look for "cold core" thunderstorm cases
Look for a cap
Look at depth of boundary layer for mixing of the moist layer
Look for excessive cloud cover which would reduce surface heating and instability

Table 3. ARL thunderstorm probability adjustment for high-elevation stations.

Checks for thunderstorm probability for surface pressure <850 hPa (high-elevation stations)
Look at time of day and month for statistical biases (northern and southern hemisphere)
Look at the surface-based stability to add or reduce thunderstorm probability
Check for inverted-V soundings for possible microbursts
Look at surface temperatures. If low temperature, reduces probability of thunderstorm
Look for a cap
Look at surface convergence or divergence on the grid. This helps to take in account orographical influence.
Check high latitudes. Thunderstorm probability is reduced in these areas if equations show higher probability.

5.1.2 Severe Thunderstorms

The AFWA severe thunderstorm routine uses model output to determine the precipitation type. One of the options is severe thunderstorms. The routine checks the value of TPI. If this value is over 73% then it is considered a severe thunderstorm capable of producing hail, strong winds, and possibly tornadoes.

The ARL routine investigates the PW, the relative humidity (RH) from 700 to 500 hPa, winds at 2000 ft above ground level (AGL), winds at 500 hPa, and the probability of thunderstorms to determine if a storm will be severe or not. It also creates a “shear score,” which is based on winds veering with height and wind speeds increasing with height. In areas where the surface pressure is below 850 hPa, the values of 700 hPa are used instead of 850 hPa. The severe thunderstorm routine also looks at values of CAPE and LI. There are different branches of the program based on PW values and the surface elevation. Additionally, the temperature of the sounding is investigated to make certain that a minimum temperature value is met.

5.1.3 Precipitation Type

AFWA uses the routine designed by (Ramer, 1993). This technique follows a parcel of air, using the relative humidity of the column from a precipitation-generating level to the ground. The ice fraction of the parcel is modeled according to the environmental wet-bulb temperature (T_w) at each level. The ice fraction of the precipitation parcel, as it reaches the surface wet-bulb temperature, determines the precipitation type. The input of the technique is a grid-point sounding of pressure, temperature, RH, and wet-bulb temperature. These inputs are obtained from the WRF or GFS. Two preliminary checks are made using T_w temperature sounding before doing a full calculation. If $T_w > 2$ °C at the surface then liquid precipitation is assumed. A value of the saturation wet-bulb temperature (T_{wS}) is the minimum wet-bulb temperature of supercooled precipitation particles. If $T_w < T_{wS}$ for the entire sounding then snow is assumed.

If neither condition (snow or rain) is met, then the program finds the top of the precipitation-generating level. The ice fraction (I) is the basic quantity calculated for determining the precipitation type and its value is determined by the T_w. The precipitation type depends on the I of precipitation arriving at the surface and on the surface value of T_w. At the generating level, precipitation is assumed to be entirely liquid (I=0) if $T_w > T_{wS}$; otherwise, it is entirely frozen (I=1). When entirely liquid, precipitation will not begin to freeze until it falls to a level where $T_w < T_{wS}$, and once entirely frozen, it will not begin to melt until it reaches a level where the T_w is above zero. Anytime the precipitation is in a mixed phase, it can either melt or freeze. Once the precipitation is entirely frozen or melted, the calculation begins again from scratch if the precipitation falls to another level where the I may change again.

The AFWA routine will output precipitation type as rain, thunderstorms, freezing rain, mixed ice, snow, and severe thunderstorm, assuming that precipitation is forecasted by the model being used.

At the current time, ARL is using the same precipitation-type forecast as AFWA so there are no differences in the final output unless they come from the model itself.

5.1.4 Precipitation Flags

The rules used by T-IWEDA need information about fog, rain, severe weather, and snow. To accomplish this, “YES/NO” forecasts or “flags” are given values for each parameter. As an example, if fog is forecasted, a value of 1 is assigned to the fog flag. If fog is not expected, a value of 0 is assigned at the grid point for each of the two-dimensional variables.

5.2 Clouds

Currently ARL software is used for all cloud information in T-IWEDA. Of most importance are the two-dimensional products total cloud cover, cloud base height, ceiling height, and total cloud amount for each layer of model output. While there have been efforts to forecast clouds from numerical weather prediction (NWP) moisture fields, they often show little skill since model moisture forecasts are a challenge that has not advanced as quickly as some other model forecast areas. Thus, it is far more productive to forecast cloud products in a post-processor using the output of the NWP fields. Verification of cloud forecasts are extremely difficult given the limited number of observations and the human factor of determining cloud height, cloud types, and cloud amounts.

AFWA uses the Diagnostic Cloud Forecast (DCF) system. The DCF is a technique where statistical relationships between a set of predictors and predictants are developed on pre-existing data and then applied to an independent set of predictors. The DCF was made operational at AFWA in 2008 to generate global cloud products. A total of 102 NWP-based predictors are generated for every forecast period. The choice of predictors includes moisture variables and parameters related to moisture. The predictor/predictant pairs are subjected to multiple discriminate analysis and linear regression (Henderson and Nehrkorn, 2009).

It was found in work by Norquist (2000) that the DCF algorithm used a forward stepwise regression scheme to select a subset of predictors from the larger pool of predictors. The regression scheme identified those predictors most closely correlated with cloud cover in each cloud deck and total cloud. RH was prominent among predictors selected; however, other variables such as static stability and wind shear were also found to be important.

Rather than using only a statistical method to make cloud forecasts ARL approached the problem with a cross between empirical techniques, statistical data, and rule-based IF-THEN sets of code (Passner, 2003). Work done by Walcek (1993) indicated a 2 to 3% increase in RH could lead to a 15% increase in cloud cover. Meanwhile, Schultz (1992) observed cases where forecasted layers of 55% RH were sometimes related to cloudy conditions. These trends were seen at ARL as cloud cover was observed when RH was well below saturation, especially with increasing time after model initialization.

The ARL software requires that cloud forecasts be converted into eights such that 1/8 to 4/8 cloud cover is considered “scattered” clouds, 5/8 to 7/8 cloud cover is “broken” and 8/8 represents “overcast.” The cloud program is broken into “warm” season and “cold” season clouds that are subdivided into tropical and mid-latitude cloud forecasts. The software first calculates the RH for each layer at each grid point. The program divides the atmosphere into layers based on height AGL. The layers used are 61–600-m, 600–1220-m, 1220–2592-m, 2592–6098-m, and 6098–8841-m AGL. These roughly are equated to low (to 1200-m AGL), middle (1220–6098-m AGL), and high cloud layers (>6098-m AGL). The cloud fraction is determined mainly by the RH of each layer, which was developed through a long-term statistical evaluation of clouds based on sounding data against observations.

Some biases and errors were found in this methodology, thus error checks were established for consistency. The fog layer was also checked to ascertain that it extended high enough off the ground to be considered more than ground fog.

5.3 Visibility

Visibility is another example of a weather hazard that impacts military ground and air operations. Both the AFWA and ARL visibility equations were developed using regression equations. In an effort to compile a database for deriving a visibility equation, Knapp (1996) collected 2790 surface observations from July 1994 to April 1995. He included station elevation, temperature and dew point, dew-point depression, RH, wind speed, ceiling height, and precipitation as his set of variables. Based on these surface observations, regression equations were formulated.

The AFWA routine is based on surface relative humidity using the following regression equation:

$$VIS=800*(101-1*RHC)/(RHC**1.75). \qquad (5)$$

The output is in km where RHC is surface relative humidity that is corrected with adjustments upward and downward by the presence and intensity of the following output from the WRF:

- Rain–adds up to approximately 25% to RHC
- Snow–adds up to approximately 25% to RHC
- Cloud water–adds up to 25% to RHC
- Upward Vertical Velocity–adds up to 15% to RHC
- Low-level wind shear–subtracts up to 13% from the RHC
- Low humidity in upper boundary layer–subtracts up to 15% from the RHC
- Mid-level clouds–subtracts up to 10% from the RHC
- Downward vertical velocity–subtracts up to 15% from the RHC

The visibility is raised or lowered based on the presence of conditions favorable or unfavorable for low visibility.

ARL used two equations in a similar fashion to the one used by AFWA. The first equation was used when the cloud ceiling is known but precipitation is not available from model output. The second equation was activated when the cloud ceiling is known and precipitation data is available.

Screening regression techniques using stepwise procedures were used to determine the predictor values for each equation type. Once the "best" correlated predictor was found, other predictors were then included to achieve the best statistical results. As an example, the equation used with known ceilings and no precipitation falling:

$$\begin{gathered} VISCAT=7.41+(0.0005*ELEV)–(0.0088*DEWPT)–(0.0371*RH) \\ +(0.0268*WINDSP)+(0.0044*CIG). \end{gathered} \tag{6}$$

Where VISCAT is the category of the predicted surface visibility, ELEV is the surface elevation, DEWPT is the surface dew point, WINDSPD is the surface wind speed, and CIG is the height of the cloud ceiling. For each equation, empirical adjustments are made based on the ceiling and surface visibility. A final check uses the model output precipitation type and precipitation rates. For example, heavy snow will act to lower the visibility result, since there is bias to overforecast visibility in that condition.

5.4 Icing

Icing conditions exist when the air contains droplets of supercooled liquid water; icing conditions are characterized quantitatively by the average droplet size, the liquid water content, and the air temperature. These parameters affect the extent and speed with which ice will form on an aircraft. Qualitatively, pilot reports indicate icing conditions in terms of their effect upon the aircraft, and will be dependent upon the capabilities of the aircraft. Different aircraft may report the same quantitative conditions as different levels of icing as a result. Clear icing is when supercooled water droplets, or freezing rain strike a surface but do not freeze instantly. Rime ice is rough and opaque, formed by supercooled drops rapidly freezing on impact. Forming mostly along an airfoil's stagnation point, it generally conforms to the shape of the airfoil. Mixed ice is a combination of clear and rime ice (see Wikipedia site in references).

Icing intensity is difficult to measure but a general definition for icing intensity can give information on how aircraft might react to the different intensities. A trace of ice means that ice becomes perceptible. Thus, the rate of accumulation is greater than the rate of sublimation. It is not hazardous unless the aircraft spends more than an hour in this environment. Light icing is when the rate of accumulation in the icing is over an hour. Moderate icing occurs when the rate of accumulation is such that even short encounters become hazardous and use of deicing equipment is necessary. Severe icing occurs when the rate of accumulation is such that deicing/anti-icing fails to reduce or control the hazard.

AFWA is using an explicit microphysics icing module developed at the National Center of Atmospheric Research (NCAR) and later implemented by AFWA meteorologists. The routine determines four icing regimes; stable icing, unstable icing, warm icing, freeze icing. These are essentially methods in which the icing can be developed and this part of the software is a "YES/NO" forecast of icing for each grid point and model output level. Stable icing occurs when the temperature is between –16 and 0 °C with a RH greater than 63%. Unstable icing is where an unstable lapse rate exists below a level in question and the maximum RH is greater than 65% while the level in question has a RH greater than 56% and temperature between –20 and 0 °C. Warm icing is an attempt to identify a warm stratus type cloud with temperatures between –12 and 0 °C with no overlaying cloud that may be seeding it. The freeze icing regime mimics freezing rain and checks that the temperature at the level is less than 0 °C and RH is greater than 80% while the temperature above is greater than 0 °C with RH greater than 80% somewhere above the level being investigated. AFWA also created an icing intensity forecast based on liquid water content amounts. These were classified into "none," "light," "moderate," and "severe" icing.

The ARL icing tool was based originally on the radiosonde upper-air observation (RAOB) icing tool developed at AFWA in 1980. The RAOB technique uses the temperature, dew-point depression, and lapse rate as a measure of instability of the layer (Forecasters Guide on Aircraft Icing, 1980).

The icing output was divided into trace, light, moderate, and severe intensities. Additionally, three icing types were calculated; rime, clear, and mixed icing. The icing type was determined using the temperature, dew-point depression, and lapse rate. There were three temperature groups: –35 to –16 °C, –16 to –8 °C, and –8 to –1 °C. These temperature classes are based on the theory of ice formation, with the first one, –35 to –16 °C, resulting in light rime icing in all classes. The middle class, –16 to –8 °C, generally accounts for mixed and rime cases based on the lapse rate of the layer. The warmest class –1 to –8 °C, is often the temperature range where clear icing is found. A final case was added to account for severe clear icing, which typically occurs when a strong inversion exists so that the relatively warm water droplets spread quickly on the aircraft and cause clear icing to form.

ARL's study (Passner, 2003) noted an underforecasting bias of model moisture, thus adjustments were made to the original AFWA icing tool to account for this.

5.5 Turbulence

Forecasting clear-air turbulence (CAT) is perhaps the most complex and frustrating problem for military aviation given the small timescale and resolution that turbulence is often observed. Sometimes CAT is easy to identify such as areas in and near thunderstorms, but much of the time CAT is highly unpredictable and not well understood. Over the years numerous attempts have been made to forecast CAT, using a variety of mathematical, physical, theoretical, and meteorological approaches. The consequences of CAT are obvious; passenger comfort, damage to the aircraft, and reduction of fuel mileage being most common. In general AFWA and ARL have combined to create very similar routines to forecast turbulence.

Boyle (1990) of The U.S. Navy Fleet Numerical Meteorological and Oceanography Center (FNMOC) used the Panofsky Index (PI) to forecast low-level turbulence, where the low level is considered to be below 4,000 ft AGL. The formula for this index is:

$$\text{PI} = (\text{windspeed})^2 * (1.0 - \text{RI}/\text{RI}_{crit}) \tag{7}$$

Where RI is the Richardson number and RI_{crit} is a critical Richardson number empirically found to be 10.0 for the FNMOC data. The higher the Panofsky Index the greater the intensity of turbulence at low levels.

Ellrod and Knapp (1992) listed environments where significant CAT was found to be prevalent. Their study associated vertical wind shear (VWS), deformation (DEF), and convergence (CVG) into a single index as shown below in equation 8 which is called the Turbulence Index (TI).

$$TI = VWS * [DEF + CVG] \tag{8}$$

The deformation term is a combination of stretching deformation and shearing deformation.

Originally, of all the methods used to forecast turbulence using a single sounding, the RI seemed to make the most sense physically, since it included the influence of both the temperature and shear in the atmosphere. Based on the work of McCann (1993), the RI also displayed the most skill of several methods tested. However, Passner (2000) found in his study between 1995 and 1997 that the PI provided more skill than the RI in the lowest 4000 ft AGL using upper-air observation data alone. Additionally, results showed that the RI was generally ineffective between 5,000 and 10,000 ft AGL and although it was more effective above 10,000 ft AGL it underforecasted turbulence at all levels. Knapp (1995) noted that the TI was based on the frontogensis equation and the results of his work indicated that DEF+CVG correlated best in the low levels which implied that horizontal wind flow changes were more vital than vertical motion fields in determining turbulence in the low levels. It was decided to combine the PI and TI for use in mesoscale model output. AFWA used the PI below 10000 ft AGL and the TI above 10,000 ft AGL as the way to calculate turbulence from model output. The turbulence intensity from the TI was based on the following numbers:

- Smooth/No turbulence TI is 0.0 to 3.0
- Light turbulence TI 3.0 to 9.0
- Moderate Turbulence TI is 9.0 to 14.0
- Severe Turbulence TI>14.0

For the lower levels using the PI

- No Turbulence PI<20.0
- Light Turbulence 20 to 100.0
- Moderate Turbulence 100.0 to 250.0
- Severe Turbulence PI>250.0

ARL uses both the PI and TI to determine turbulence severity. However, ARL uses the PI below 4000 ft AGL and TI above 4000 ft AGL. The other significant difference is that ARL adds some “checks” when the calculation of turbulence appears suspect. TI appeared to overforecast turbulence in the mid-levels so some additional “rules” were put into the software to deal with these biases. ARL also increases the turbulence in the boundary layer when surface temperatures are high and when surface winds are high. Normally, these cases are handled by the RI and Panofsky Index but in the rare circumstances when the mathematical equations miss, there are checks to make sure that the turbulence forecast more accurate.

5.6 Other Variables

There are a number of two- and three-dimensional variables that are needed by T-IWEDA. Most of these are simple parameters and are determined directly or with minor unit conversions from the model output. As an example, air temperature, dew-point temperature, dew-point depression, and potential temperature are all easily derived. It cannot be assumed that since ARL and AFWA are both running WRF-ARW that the results of the temperature fields (and other output fields) will be exactly the same. Since AFWA may be using a 15-km horizontal resolution and ARL may be using a 1-km resolution, there may be slight differences in derived parameters such as temperature, wind speed, dew point, or wind direction. Additionally, AFWA and ARL may be using different parameterizations, although efforts were made by ARL to use many of the same parameterizations as AFWA does. Differences in model fields should not be significant, but will exist.

5.6.1 Density Altitude

There are many different ways to calculate density altitude. AFWA's method is currently being used by ARL. The calculation of density altitude is shown in equation 9:

$$DA = 145{,}442.16\left[1 - \left(\frac{17.326 * (P * 0.29532)}{(1.8 * T_v - 273.16)}\right)^{0.235}\right] \tag{9}$$

Where DA is the density altitude in feet, P is the pressure in hPa, and T_v is the virtual temperature in degrees K.

5.6.2 Inversion Height

This value is calculated by ARL only and is not available from AFWA. To calculate the inversion height, start above the ground (model level 2) and search the temperature vertically at each grid point. When the point sounding begins to warm, it is considered to be the lowest point of the inversion. Continue to search until the temperature again cools. A check is done to make sure that the layer is more than 20-m deep, the amount of temperature cooling is greater than 0.10 °C, and the inversion heights is less than 7000-m AGL.

5.6.3 Illumination

This variable is calculated by ARL only and is not available from AFWA. The illumination at each horizontal grid point is calculated in millilux (Duncan and Sauter, 1987). The software needs the year, month, day, minute, latitude, longitude, high cloud, middle cloud, low cloud, precipitation type, snow depth, cloud type, fog data, and thunderstorm probability. Albedo is calculated based on snow depth. The illumination routine uses tables or values to make a calculation how much illumination there is based on the clouds, time, and weather influences.

5.6.4 Wind Variables

ARL receives the U and V wind components from AFWA from both the WRF and GFS. From there, the wind direction, and wind speed are post-processed using ARL derivations. The wind gust routine for the WRF is received from AFWA, but for the GFS, it is post-processed at ARL; however, the same software is used for both model outputs. The calculations for wind speed and wind direction are rudimentary and come from the U and V wind components. The wind gust procedure is much more complicated because it accounts for both convective wind gusts and non-convective winds.

The non-convective wind gust routine first finds the average wind speed from the surface to top of the PBL. Then the software routine searches for the maximum wind speed in the PBL for the first statically stable layer upward from the surface. It is assumed that this value is brought to the surface.

If the convective precipitation derived from the model is greater than 0.01, McCann's (1994) Wind Index (WINDEX) is applied. The WINDEX routine is generally designed to forecast the dry microburst winds associated with convection. If the freezing level is at the surface the maximum convective gust is kept as the surface wind. The software searches for the height of the freezing level, the mixing ratio at the melting level, the lapse rate from the surface to the melting level, the mean mixing ratio from the surface to 1-km AGL, the mixing ratio at 1 km, water vapor mixing ratio from the surface to 1 km. The combination of these variables is weighted and a final value of the surface wind gust is derived.

6. Conclusions

A Tri-service version of the IWEDA software has been developed and fielded on Army, Air Force, and Navy systems. Meteorological data is provided to the T-IWEDA from both the WRF and GFS output. Typically the WRF is used for short-range forecasts while the GFS is used for longer-range forecasts. The models provide meteorological output for temperature, pressure, moisture, wind, precipitation amounts, and many other variables; however, many of the weather variables needed by the T-IWEDA are not available directly from the models. These variables include many key parameters such as icing, turbulence, surface visibility, cloud heights, and thunderstorm probability. To meet the needs of T-IWEDA, these parameters are formulated by ARL and AFWA after the model is completed, or in a post-processed manner. While many of the techniques used by ARL and AFWA are similar, the goals of AFWA and Army weather are dissimilar; with the Army needing weather information at smaller scales in both time and space. Thus, there are differences in the way they approach the post-processing variables and it becomes essential to investigate how and why AFWA and ARL develop post-processed parameters. The goal of this project was not to find the best method for each variable but to point out how the Army and Air Force approach the post-processing problem and the theory behind many of the essential parameters for T-IWEDA. Model differences will exist as ARL continues to work toward reducing horizontal resolutions, increase vertical resolutions, and tailor the products for even shorter time resolution. Future research will be done on how these model influences change the post-processing routines and what future adjustments must be made to run the T-IWEDA and other tactical decision aid with even higher confidence and to attain better results.

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List of Symbols, Abbreviations, and Acronyms

AFWA	U.S. Air Force Weather Agency
AGL	above ground level
ARL	U.S. Army Research Laboratory
BLI	Best Lifted Index
CAPE	convective available potential energy
CAT	clear-air turbulence
CIG	ceiling
CVG	convergence
CWT	Combat Weather Teams
DA	density altitude
DCF	Diagnostic Cloud Forecast
DEF	deformation
DEWPT	surface dew point
ELEV	surface elevation
etap	eta-pressure
FNMOC	Fleet Numerical Meteorological and Oceanography Center
GFS	Global Forecast System
hPa	hecto-Pascal
I	ice fraction
IMETS	Integrated Meteorological System
IWEDA	Integrated Weather Effects Decision Aid
JMBL	Joint METOC Broker Language
JMCDM	Joint METOC Conceptual Data Model
LI	lifted index
METOC	Mission Essential Meteorological and Oceanographic Center

NCAR	National Center for Atmospheric Research
NCEP	National Center of Environmental Prediction
NWP	numerical weather prediction
PBL	Planetary Boundary Layer
PI	Panofsky Index
PW	precipitable water
RAOB	radiosonde upper-air observation
RH	relative humidity
RHAVE	Relative Humidity Average
RHC	surface relative humidity
RI	Richardson number
RI_{crit}	critical Richardson number
RRTM	Rapid Radiative Transfer Model
SWEAT	Severe Weather Threat (*Index)*
TI	Turbulence Index
T-IWFDA	Tri-Service Integrated Weather Effects Decision Aid
TPI	Thunderstorm Prediction Index
TT	Total Totals Index
T_v	virtual temperature
T_w	wet-bulb temperature
T_{wS}	saturation wet-bulb temperature
UTC	Coordinated Universal Time
VWS	vertical wind shear
WINDEX	Wind Index
WINDSP	surface wind speed
WRE-N	Weather Running Estimate-Nowcast
WRF	Weather Research and Forecasting (*model*)

WRF-ARW	Advanced Research version of the Weather Research and Forecasting model
WSM-5	WRF Single Moment-5

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